THE BEARING OF PROGRESSIVE INCREASE OF VISCOSITY DURING INTRUSION ON THE FORM OF LACCOLITHS

SIDNEY PAIGE[1]
United States Geological Survey

The attention of geologists has been called on several occasions to the laccolithic intrusive bodies of the northern Black Hills, South Dakota. Russell[2] has described and offered explanations for a number of the phenomena there observed. Jaggar and Howe[3] have published a detailed account of the region and performed experiments illustrating the processes which are believed to have led to the formation of laccolithic intrusive bodies; and others have commented on the work of these men, in discussing other regions where similar phenomena may be observed. The classic work of Gilbert[4] and the equally careful studies of Pirsson and Weed,[5] Cross,[6] and others have contributed to placing the theory of laccolithic intrusion on a firm basis. The type of laccolithic structure about to be described has certain peculiarities, to explain which the writer resorted to speculation and came to conclusions for which he later found partial support in the accounts of earlier writers, particularly Pirsson. In the case in point the process which is invoked as an

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[2] Israel C. Russell, "Igneous Intrusions in the Neighborhood of the Black Hills of Dakota," *Jour. Geol.*, IV (1896), 23–43.

[3] T. A. Jaggar, Jr., *The Laccoliths of the Black Hills;* Ernest Howe, "A Chapter on Experiments Illustrating Intrusion and Erosion," *Twenty-first Ann. Rept. U.S. Geol. Survey*, Pt. 3 (1901), pp. 165–303.

[4] G. K. Gilbert, "Geology of the Henry Mountains," *U.S. Geographical and Geological Survey of the Rocky Mountains Region*, 1880.

[5] W. H. Weed and L. V. Pirsson, "Geology and Mineral Resources of Judith Mountains of Montana," *Eighteenth Ann. Rept. U.S. Geol. Survey*, Pt. 3 (1898), pp. 445–614.

[6] Whitman Cross, "The Laccolitic Mountain Groups of Colorado, Utah, and Arizona," *Fourteenth Ann. Rept. U.S. Geol. Survey*, Pt. 2 (1892–93), pp. 165–258.

important factor in determining the form of certain laccoliths—increasing viscosity during intrusion—is believed to have been carried to its ultimate results. Since this phase of the discussion has not been presented before in a connected way, the writer hopes the following notes may be of interest.

Near the northwest corner of Spearfish quadrangle in the Black Hills of South Dakota, Crow Peak reaches an elevation of 5,785 ft. This peak is the crowning point of a rugged, sharply dissected, isolated mountain about $1\frac{1}{2}$ miles long and a mile wide, its larger dimension lying north-northwest.

The mountain owes its presence to an intrusive mass of quartz monzonite porphyry. This porphyry outcrops as an elliptical area with its longer diameter (about a mile) trending north-northwest. Where the porphyry breaks through the overlying sedimentary rocks the strata have been bent sharply upward and steep dips (up to 90°) are found at all points on the periphery of the intrusion. These dips become much gentler a short distance from the intrusion and within a half-mile or less the beds have assumed the nearly horizontal attitude prevalent over this region.

There is strong presumptive evidence, however, that the igneous mass has a tongue-like extension northwestward beneath the sedimentary rocks, for the axis of a clearly defined anticline extends in this direction for several miles from the base of the mountain. Such an extension is not indicated to the southward.

The sedimentary rocks involved at this place rest upon a pre-Cambrian basement and are as follows: Cambrian quartzite, sandstone, and shale (Deadwood formation), almost invariably a thin shale at the top above a thin quartzite, 400 ft. ±; Ordovician limestone (Whitewood), 80 ft. ±; Carboniferous: shaly Englewood limestone at base 30 ft. ±; overlain by Pahasapa limestone, 550 ft. ±; succeeded by Minnelusa sandstone, 400 ft. ±; in all 1,460 ft. ±.

A conception of the mechanics of the intrusion must be in large part based upon speculation, for data are not at hand even to definitely establish the underground form of this igneous mass. As may be seen on the map (see Fig. 1), the northern half of the intrusion cuts as high in the sedimentary beds as the base of the

Whitewood limestone. Lowest Cambrian strata are reported by Jaggar, in a tunnel, on the north end of the mountain.[1] On most of the southern half of the porphyry, however, the intrusion reaches the Pahasapa limestone, while at the extreme southern end the Minnelusa sandstone is cut by the igneous rock. Near this latter locality a small mass of Cambrian sandstone was observed, so situ-

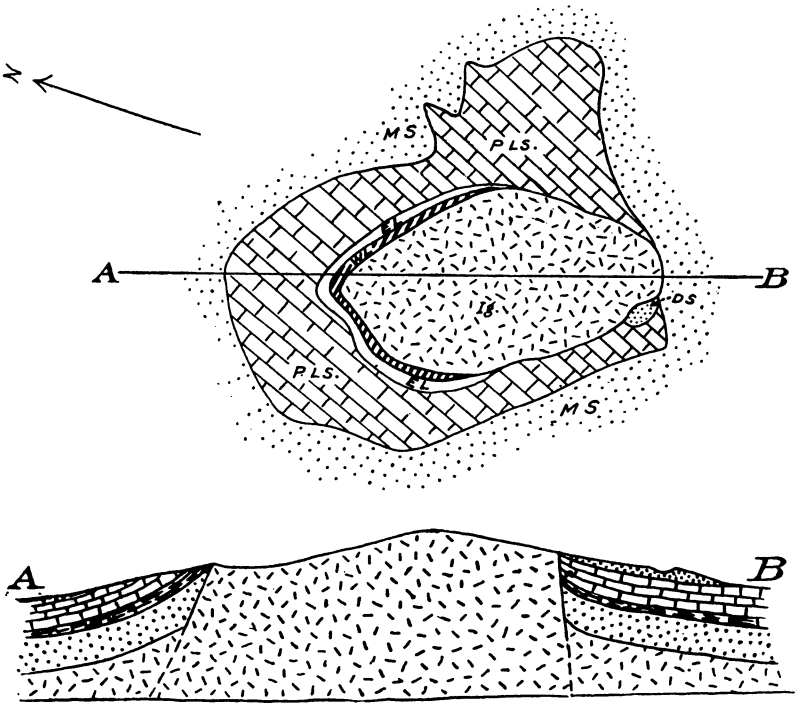


FIG. 1.—Geologic map and cross-section of Crow Peak (Paige): DS, sandstone of Deadwood formation; WL, Whitewood limestone; EL, Englewood limestone; PLS, Pahasapa limestone; MS, Minnelusa sandstone.

ated that only faulting could explain its presence. As figured by Jaggar, both in plan and in cross-section the impression is given that this mass is a symmetrical laccolith either within the Deadwood formation or between the Deadwood and the underlying schists. The cross-section especially suggests that the sedimentary

[1] T. A. Jaggar, Jr., "The Laccoliths of the Black Hills," *Twenty-first Ann. Rept. U.S. Geol. Survey*, Pt. 3 (1901), p. 242.

strata once passed unbroken over a steep dome. In fact, Jaggar refers to this mountain as a type of steep-dome laccolith.

The facts presented above (Fig. 1) show that this is not strictly the case. The intrusive evidently cross-cuts much of the Cambrian section at the northern end of the porphyry, while at the southern end even the Whitewood, Englewood, and Pahasapa limestones are transected. The presence of a small mass of Cambrian sandstone lying against the porphyry on the one hand and the Minnelusa sandstone on the other hand adds weight to this idea that the magma violently forced its way through this portion of the overlying strata much as a punch might perforate plastic material. It is probable that such evidence of violent dislocation decidedly influenced the conclusions of Russell when he termed these masses igneous plugs. Considerations which take into account, however, the configuration of a great number of intrusive bodies in this region, and an examination of the surface structure in the region about Crow Peak leave little ground for supposing that this Crow Peak uplift is different in its broad essentials from these other laccolithic bodies, and it only remains, therefore, to discuss and offer a plausible explanation for its difference in detail, that is, the evidently violent rupture of its summit and the particular curve which the dips of the sedimentary cover would indicate that the magma possesses beneath its covering strata.

It is of interest first to call attention to a fundamental difference in the character of the curve on the upper surface or flanks of the Henry Mountains laccoliths and that on many of the Judith Mountain laccoliths, Montana. Pirsson[1] has noted this difference but does not comment upon it at length. The ideal cross-section of the laccoliths of Mount Holmes[2] (see Fig. 2) as drawn by Gilbert after a careful study of the field may be compared with a typical cross-section as drawn by Pirsson[3] (see Fig. 3) of Judith Mountain. While the cross-section of the upper surface as pictured by Gilbert is everywhere convex upward, that pictured by Pirsson is locally very straight or slightly concave upward.

[1] *Op. cit.*, p. 580.

[2] Opposite p. 28.

[3] *Op. cit.*, Plate LXXXII, section A.–A.

The writer in seeking an explanation for the condition at Crow Peak, and led by the result of one of Howe's experiments in artificial laccolith building,[1] formulated the hypothesis that the form of the upper surface of a laccolith might be materially affected by the progressive increase in viscosity of the magma during injection.

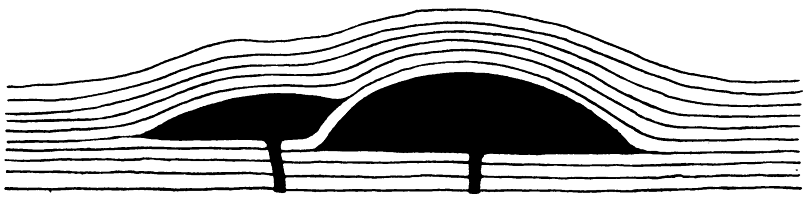


FIG. 2.—Ideal cross-section of the laccolites of Mt. Holmes (after Gilbert)

It was postulated that due to pressure from beneath, magma in fluid condition was introduced at the base of a sub-horizontal sedimentary series, and insinuated itself along the basal contact forming a thin sill or sheet of roughly circular outline. Such a sheet would exert hydrostatic pressure, which if sufficiently great to

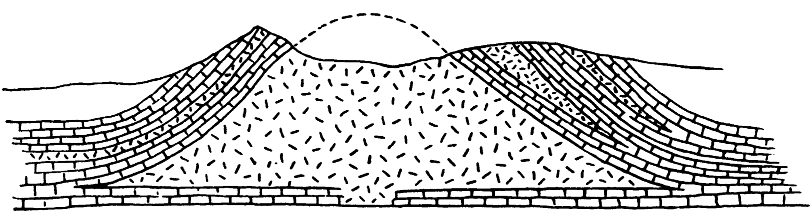


FIG. 3.—Section of laccolith in Judith Mountains (after Pirsson)

overcome the weight of the overlying strata would initiate the formation of a dome. If introduced with great rapidity such a sheet theoretically might take the form of the Shonkin Sag laccolith[2] (see Fig. 4) described by Pirsson for this form suggests that the lava, being introduced rapidly in a thin sheet, attained eventually an area over which the hydrostatic pressure was sufficiently great

[1] *Op. cit.*, experiment III.

[2] W. H. Weed and H. V. Pirsson, "Geology of the Shonkin Sag and Palisade Butte Laccoliths in the Highwood Mountains of Montana," *Am. Jour. Sci.*, 4th series, XII, 1–17.

suddenly to lift the cylindrical mass of rock above it. Pirsson reaches the conclusion that this magma was introduced rapidly, but on other grounds.[1] He says: "The occurrence of ball-like masses in the upper crust of the laccolith seems to show that the filling took place with considerable rapidity." If now it be conceived that magma was introduced more slowly or that its viscosity was greater, thereby interfering with the operation of the law of hydrostatic pressure, the factor of marginal cooling with concomitant increasing viscosity becomes a factor of importance.

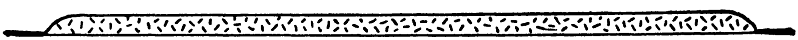


FIG. 4.—Cross-section of Shonkin Sag laccolith (after Pirsson)

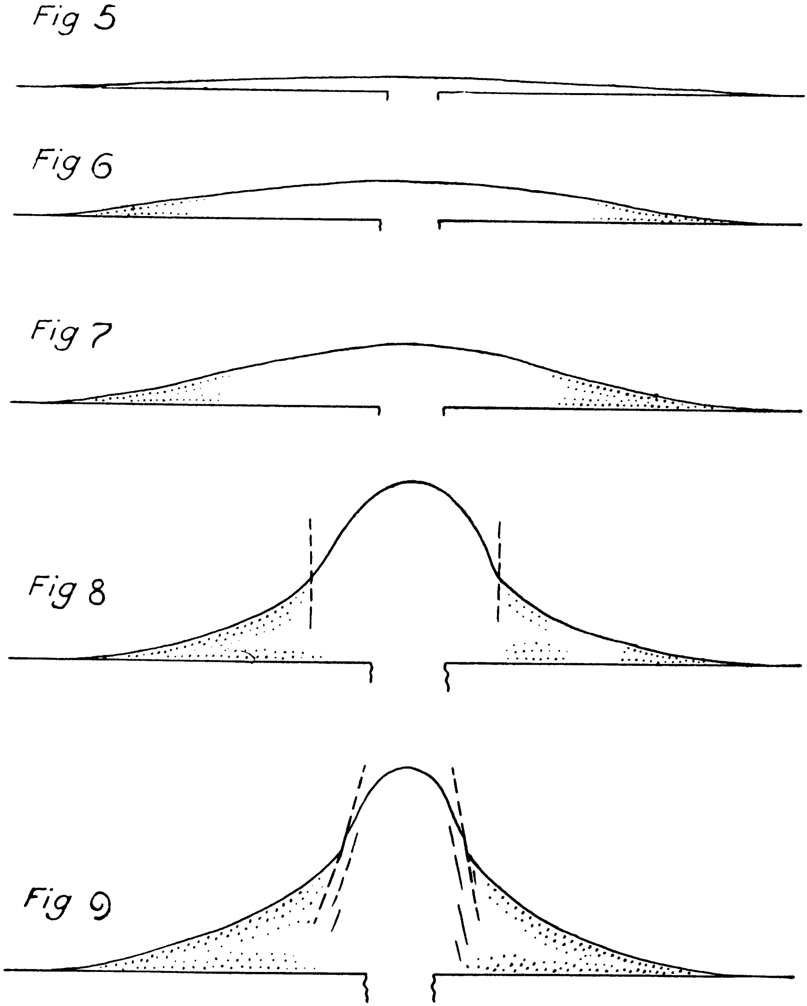
For just as much as the law of hydrostatic pressure is prevented from acting or forced to act more slowly, just so much will there be unequal distribution of upward pressure. The region of greatest pressure will be where the magma is most fluid, i.e., directly over the source of supply, while from this region outward, decreasing pressure will be exerted on the roof. The series of diagrams (Figs. 5–9) illustrate what might take place during intrusion under such conditions. The outer border congealing first, the area of perfectly transmitted pressure would be reduced, and each successive[2] application of pressure would therefore serve to accentuate the upward curve of the strata, that is, the curve on the surface of the laccolithic flanks in such a system would be more or less concave upward.

At one end of the series, then, we would have the Shonkin Sag type with a flat top; under condition of intermediate viscosity the type depicted by Gilbert (where the progressive increase of viscosity was not sufficient to form a curve concave upward, though sufficient to prevent a flat roof); and at the other extreme the type which the Judith Mountain masses approach and which Crow Peak may possess in even greater perfection.

[1] *Op. cit.*, p. 12.

[2] The process was probably continuous in its effect but successive steps are used to express more clearly the idea.

If now this system be carried to its ultimate end what will result? Obviously the dips of the sedimentary strata will approach



FIGS. 5–9.—Series of diagrams illustrating the effect of marginal cooling and increasing viscosity on the curve of a laccolithic surface.

the vertical, and if the central portion of the igneous mass is still competent to transmit pressure either by hydrostatic means or by direct thrust through a central core now become very viscous, it

is quite possible that breaks will occur and their configuration will be more or less circular—the fault surface more or less cylindrical.

It is this end which is believed to have been reached at Crow Peak. In this connection attention is again directed to the horizon against which much of the intrusion now rests, viz., soft shale of the Deadwood formation, and to the small fragment of sandstone of the Deadwood formation faulted against Minnelusa sandstone at the southern end of the intrusive mass. The shale of the Deadwood formation would form an ideal locus for such a break as is hypothesized after the beds had assumed high dips; and the block of sandstone of the Deadwood formation may well represent material dragged up along a fault plane.

Iddings says:[1]

> But when vertical displacement with faulting is one of the chief characteristics of the intrusion a distinction from normal laccolithic intrusion should be recognized. In the extreme this would result in the forcing upward of a more or less circular cone or cylinder of rocks which might be driven out at the surface of the earth, not necessarily in a coherent condition, or might be arrested at any stage of such extrusion and so might terminate in a dome of strata resembling the dome over a laccolith. By this mode of intrusion the vertical dimension of the intruded mass becomes still greater as compared with the lateral dimensions, so that its shape is more that of a plug or core.
>
> Such an intruded plug of igneous rock may be termed a bysmalith. There is then a transition from a flat intrusive sheet to a laccolith with lenticular form and from this to a bysmalith with much greater depth and considerable vertical displacement.

Jaggar in commenting on the description of Mount Holmes by Iddings, says:[2] "The sections and the text indicate that the mass described resembles the steep-sided laccoliths of the Black Hills and that it breaks across strata in the manner of a stock."

Before summing up, specific reference should be made to the work of Pirsson. He says:[3]

> It is of interest to note that the convexity of a laccolith is not a necessary function of its depth but of the viscosity of the lava in relation to the other factors; hence laccoliths of various shapes and sizes may be found in the same horizon. We have seen this, from the present work, as occurring in the Judith Mountains.

[1] J. P. Iddings, "Bysmaliths," *Jour. Geol.*, VI (1898), 705.

[2] *Op. cit.*, p. 289.

[3] *Op. cit.*, pp. 585–86.

It also seems evident that the rate of supply, or the time within which the force acts, must have a bearing in this case, and it is imaginable that the upward propulsion of the magma might be so rapid that a small laccolith could be formed where the arch of the strata was such that it was within the limits of plasticity and would tend to maintain itself after the upward force ceased, even though the magma was in an extremely liquid state.

Also, there is with a given source of supply and a given viscosity a certain limit beyond which a lava cannot form a sheet, but, if the supply of material continues, must form a laccolith. For at a certain radial distance from the supply the internal viscosity, assuming even that its ratio remains the same, will check the transmission of pressure and the onward-propelling, splitting force of the lava; but, the supply continuing, the strata must uparch and form a laccolith.

Pirsson recognized other factors in the problem besides that of viscosity, but they have not a direct bearing here. If any contribution is made at this time, it lies in the suggestion of the function of *progressive* increase of viscosity and its effect on form and in suggesting that, though varying end results may seem to be types which at first sight call for separate classification, they are in fact but stages in a process, the underlying forces of which are generically alike. To be precise: If we select Crow Peak as a type which superficially has characteristics of a volcanic plug as hypothesized by Russell (from descriptions of Newton and Winchell), we reach the conclusion that on a laccolith there was developed a form truly pluglike and that faulting is present of a sort fitting well that which circumscribes a bysmalith. And we suggest that such a cycle of phenomena may be in large measure the result of progressive increase of viscosity during the intrusion of a laccolithic mass; and further, that a series with Shonkin Sag at one end, the convex forms of the Henry Mountains in an intermediate portion, and the concave forms of the Judith Mountains at the other end, may be due largely to the same influence.